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Trajectory Planning of Welding Robot Based on Terminal Priority Planning

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Abstract: In order to improve the trajectory planning efficiency and accuracy of multi-joint welding robot, according to the movement feature of multi-joint welding robot, the paper analyzed on existing problems in spatial joint planning of the robot, proposed a terminal priority planning method of robot joint planning, based on the study of energy conservation and accuracy of robot terminal. Using this method, the paper proceeded planning of welding robot joint, stated implementation procedure of joint planning, conducted simulated test simulating welding robot, the result demonstrated that the research is of high feasibility and technological application values. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Welding robot, Trajectory planning, Terminal priority planning, Energy conservation, Accuracy.

1. Introductions

Joint-space trajectory planning commonly adopt Cartesian model [1], but this model has some degenerate problems, such as complicated calculation, unable to deal with changing environment and uncertain factor, and so on. For the past few years robot trajectory planning has acquired many research achievement [2-7], for example, probabilistic roadmap method PRM and rapidly-exploring random trees RRT [8], apply to high redundant robot trajectory planning. Reference [9] researched on the manipulator of given manipulator terminal task; it planned a free path for mobile manipulator. Reference [10] researched on energy consumption of manipulator and presented an approximate algorithm of minimal energy consumption. Reference [11] completed joint-space trajectory planning by real-time interpolation algorithm.

However, the researches above are all conducted on the condition of meet the planning requirement and lack of study in the mass and energy distribution.

On the basis of the movement feature of multi-joint welding robot and principle of energy configuration, the paper analyzed on energy conservation and improving terminal accuracy, proposed a terminal priority planning method of robot trajectory planning, it can simplify the Cartesian equations of motion during the joint planning of welding robot, optimize the movements of the joints, solved existing problems, improved the fitting precision of robot space trajectory, and achieved reasonable distribution of welding robot's energy.

The trajectory planning method can not only realize joint-space trajectory planning of welding robot, but also can be applied to other multi-axis systems especially joint-space planning of redundant robots.

2. Principle of Terminal Priority Planning

Welding robot is usually multi-DOF and multi-joint manipulator. During the welding process, the end joint has lightest weight, needs least motion energy, the motion energy configured goes higher as the series of joint and terminal increases. At the meantime, rotation angle of the joints in the joint planning are usually obtained by Cartesian equation, maybe there're multiple solutions in the actual planning, it will make the planning result space of robot especially multi-DOF redundant robot larger, equates the motion probability of the joints, and the joints have to move in every step adjustment, such solutions usually are not the shortest and most energy-efficient path of robot step adjustment. In the second place, in order to improve the trajectory running accuracy, we can increase step number and reduce stepover in interpolation planning, in the general sense, reduction of stepover can improve the accuracy of trajectory, but it needs the coordination between motor accuracy and machine accuracy, so when the stepover is reduced to a certain value, it can not only improve the interpolation accuracy, but also make the robot vibrate larger, it is disadvantage of robot working steadily. Then using Cartesian movement planning may lead to a situation that terminal planning is stable but deviation angle of other joint is much higher, although it can meet requirements of starting point and terminal point, but it may cause vibration and even increasing error during the movement, it is bad for welding accuracy maintaining. In the last place not all the joints will participate in the movement adjustment in a step adjustment. In many cases it only needs two-stage or multistage joints next to the terminal to take part in the motion adjustment. If it could accomplish joint motion adjustment of one step by this way, then other joints don't need to participate, so the shortest path planning and minimum energy configuration can be realized.

In conclusion, when we tried to conduct joint planning by Cartesian equation, we began with terminal joint, determine the movement rotation angle of robot terminal joint planning, then preferentially planned the movement rotation angle of the second and third terminal joint in turn, at last determined the movement rotation angle of robot base joint. So as to make the joint planning with minimum energy, shortest path, perfect running status, and optimum angle value of joints planning movement. As the planning was started from terminal joint priority of robot, so we called this joint planning method terminal priority planning.

3. Implementation of Terminal Priority Planning

3.1. Implementation of Terminal Joint Priority Planning

During the planning of welding robot, it should meet the requirement of welding trajectory accuracy Δ; the accuracy is determined by the motion state of robot terminal manipulator. As Fig. 1 shows, the dotted line stands for the planning trajectory, O stands for robot terminal joint axis, OA stands for the initial position of robot terminal planning, OB stands for the final position of robot terminal planning, $\Delta\theta$ stands for rotation angle of robot step planning, ΔL stands for the stepover. In order to maintain the welding accuracy Δ, stepover of robot trajectory planning $\Delta \mathrm{L}$ should less than welding accuracy Δ. After stepover ΔL determined, as the length of manipulator terminal joint has determined, so $\Delta\theta$ is determined. Because the stepover ΔL is very short actually, the difference between OB and OA is not big, so let $|\mathrm{OA}| = |\mathrm{OB}|$, then the value of $\Delta\theta$ could be obtained by arc angle, i.e.

$$\Delta\theta = \frac{360\Delta\theta}{2\pi|\mathrm{OA}|} = \frac{180\Delta\theta}{\pi|\mathrm{OA}|} \tag{1}$$

There are errors between value of $\Delta\theta$ obtained by this method and actual position value, it is less than the actual value, but this method is under the premise of fulfilling accuracy Δ, so this method must meet the requirement of robot accuracy.

After the value of $\Delta\theta$ is determined, suppose position angle of position A on manipulator terminal joint is θ_A, then the position rotation angle θ_B of position B is

$$\theta_\mathrm{B} = \theta_\mathrm{A} + \Delta\theta, \tag{2}$$

where θ_A, θ_B are equal to the inverse solution of Cartesian motion equations corresponding to position A and position B on manipulator terminal joint, then when we proceed Interpolation planning of welding robot joints, the inverse solution of Cartesian motion equations corresponding to position on the manipulator terminal joint θ_n is determined, it is equal to θ_B. So we determined the inverse solution of Cartesian motion equations corresponding to manipulator terminal joint by terminal priority planning.

In addition, during the joint planning, we always encounter the circumstance that terminal planning joint in place, but angular displacement of middle joint in some step is oversize. When we encounter this situation by using terminal priority planning, we increase proper stepover in this step, by equidistance increasing or equidistance increasing, in accordance with specific conditions. As the planning step has fulfilled the welding accuracy, so the increase of stepover in this step will not affect the welding accuracy. We can also use another way to solve the problem, we can replan a trajectory, take the beginning of the step as new beginning of the trajectory.

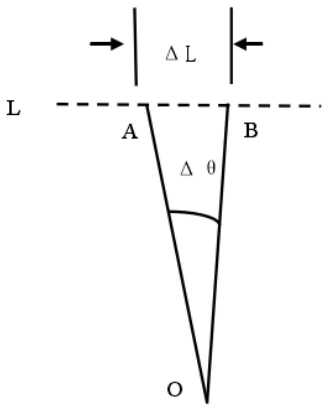

Fig. 1. The diagram of robot terminal priority planning.

When we get θ_n by terminal priority planning, the position angle of robot terminal joint can be calculated directly, but the calculation can't determine rotate direction of terminal joint, the determination of direction can be determined by the extension direction of trajectory planning on the basis of trajectory's shape shifting. Special trajectory needs to be determined by trial-and-error method, that is find two successive solution, and then calculate and verify whether it can satisfy Cartesian equation.

The analysis above is for straight trajectory. For curve trajectory, we always cut the curve into tiny straight step interpolation, so this method applies to curve trajectory too.

3.2. Implementation of Common Joint Priority Planning

The implementation of common joint planning follows terminal priority planning method, find inverse solution of other joint beside terminal joint, i.e. finding motion inverse solution $\theta_1, \theta_2, \theta_3, \theta_4, \ldots \theta_n$ of other joint beside terminal joint by Cartesian equation. For terminal joint rotation angle θ_n of N-Dof robot, it has been determined by Eq. (1) and Eq. (2) using terminal priority method, here we'll find $\theta_1, \theta_{21}, \theta_3, \theta_4, \ldots \theta_{n-1}$.

First of all, according to the theory of Cartesian robot kinematics, we can get the transformation matrix of base coordinate system relative to N-Dof serial robot [12], i.e.

$$A_1 A_2 A_3 A_4 \ldots A_n = {}^R T_H \tag{3}$$

In Eq. (3), i = 1, 2, 3, …n, A_i stands for the matrix of relative position relation between joint i and joint i-1, it is usually represented as:

$$A_i = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_{i-1} & S\theta_i S\alpha_{i-1} & a_{i-1} C\theta_i \\ S\theta_i & C\theta_i C\alpha_{i-1} & -C\theta_i C\alpha_{i-1} & a_{i-1} S\theta_i \\ 0 & S\alpha_{i-1} & C\alpha_{i-1} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

In the matrix A_i, $s\theta_i$ stands for $\sin\theta_i$, $c\theta_i$ stands for $\cos\theta_i$, similarly, parameter d_i stands for the normal distance between joint i and joint i+1, a_i stands for the link length between joint i and joint i+1, α_i stands for the torsional angle of joint i and joint i+1, θ_i stands for the link angle of joint i and joint i+1. ${}^R T_H$ in Eq. (4) stands for the matrix of expected goal, its value can be determined in accordance with expected goal during planning.

${}^R T_H$ is usually represented as:

$${}^R T_H = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

As the rotation angle of terminal joint θ_n has determined, so the matrix A_n turns into constant matrix, marked as B_n, then the transformation matrix of base coordinate system relative to N-Dof serial robot turns into:

$$A_1 A_2 \ldots A_{n-1} B_n = {}^R T_H \tag{6}$$

Using this method to solve Cartesian motion equation, the series of equation reduces one series, so the calculation and solution is simplified. We find inverse solution of the second terminal joint θ_{n-1} by matrix (6) through terminal priority planning method.

The first step is to suppose $\theta_1, \theta_2, \ldots \theta_{n-2}$ are known, the values are current position angle, and then $A_1, A_2, \ldots, A_{n-2}$ are constant matrix, marked as $B_1, B_2, \ldots, B_{n-2}$, so the transformation matrix of base coordinate system relative to N-Dof serial robot turns into:

$$B_1 B_2 \ldots B_{n-2} A_{n-1} B_n = {}^R T_H \tag{7}$$

Only A_{n-1} corresponds to θ_{n-1} which is unknown in matrix (7), so it is easy to fine the value of θ_{n-1}. According to the theory of matrix inversion, matrix (7) turns into:

$$A_{n-1} = [B_1 B_2 \ldots B_{n-2}]^{-1} \, {}^R T_H B_n^{-1} \tag{8}$$

The second step is to solve matrix (8), determine whether there is a reasonable inverse solution θ_{n-1}. If any, the problem is solved; if not, we find the solution by matrix of the second and third terminal joint, i.e. solutions of the second and third terminal joint are unknown. Suppose others are known, similarly, matrix (7) turns into:

$$B_1 B_2 \ldots B_{n-3} A_{n-2} A_{n-1} B_n = {}^R T_H \tag{9}$$

In matrix (9), only A_{n-2} and A_{n-1} correspond to θ_{n-2} and θ_{n-1} are unknown, so according to Cartesian equation, matrix (9) turns into:

$$A_{n-2} A_{n-1} = [B_1 B_2 \ldots B_{n-3}]^{-1} \, {}^R T_H B_n^{-1} \tag{10}$$

Then find θ_{n-2} and θ_{n-1} by matrix (10).

The third step is to solve matrix, determine whether there is a reasonable inverse solution θ_{n-1}. If any, the problem is solved; if not, find the solution by matrix of the second, third and fourth terminal joint using Cartesian equation theory in a similar way, until find reasonable solution completely. The important thing to note here is we can find θ_{n-2} and θ_{n-1} by Cartesian matrix when we solve them by the second and third matrix of terminal joint, and in general the two solutions can fulfill the equation probably, but only solution θ_{n-1} is found by terminal priority method, although θ_{n-2} can fulfill the equation too, but it may not the optimal solution, so we should solve and validate them separately by the planning method above.

Finally, we can find motion solutions of all joints by terminal priority planning method, but solutions found by this way are totally different from solutions got by Cartesian equation. Especially in the motor process, using terminal priority planning method follows meeting the motion requirement of terminal manipulator first, motion first, and other joints keep still or move less, by this way it can reach that the least movement of all joints, shortest trajectory, least energy consumption during the actual implementation of robot trajectory joint planning. In the meantime it can reduce the series of kinematical equation, decrease calculation and pick up the pace of planning. Therefore this method has important technological values to multi-joint robot especially redundant robot, real-time teaching planning robot, and robots working in the energy limited place such as outer space.

4. Tests and Analysis

4.1. Data Sorting

In order to verify the terminal priority planning method, we adopt three-joint welding robot as research model, model and conduct simulation tests. In the condition of default welding speed is 35 cm/min, welding accuracy is less than 5 mm, we found manipulator model of three-joint welding robot, determine Cartesian motion parameter, establish Cartesian motion equation, planning and solve the trajectory of straight line and curve. The data of the same straight line are sorted and shown in Fig. 3 and Fig. 4. Choose two groups of the data in different beginning of manipulator. Due to space constraints, Fig. 3 and Fig. 4 only choose partial data, and extract 50 interpolation points in each group. Fig. 3 shows data extracted from the first position, Fig. 4 shows data extracted from the second position. At the same time we simulate the straight trajectory shown in Fig. 2 and curve trajectory shown in Fig. 5 to verify the terminal priority planning method.

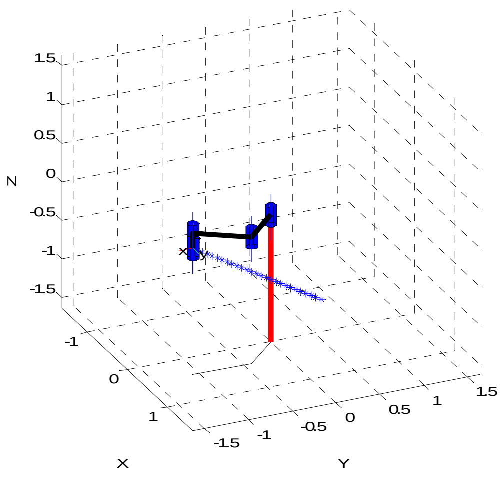

Fig. 2. Trajectory diagram of straight line interpolation.

4.2. Data Analysis

Analyzing the data in Fig. 3 and Fig. 4, θ_1, θ_2, θ_3 are Cartesian motion inverse solutions of welding robot found by terminal priority planning method, θ_3 is the solution of terminal joint position. As it is shown in Fig. 3 and Fig. 4, the varieties of θ_3 are equal, in line with principles. The varieties of θ_1 are changed a lot, there's no change in the data of former ten interpolation points and latter ten interpolation points in Fig. 3, it is stated that there's no movement in the former ten interpolation points and latter ten interpolation points of terminal joint planning during the planning in the first position of the first joint. The data of θ_1 in Fig. 1 is unchanged in all the 50 interpolation points, it is stated that the first joint didn't rotate during the interpolation process of all the second position. So by analyzing the data of Fig. 3 and Fig. 4, we could see that the first joint can keep still or move less in the interpolation process, through this way it can save energy and reducing friction and vibration, which fully embody the theory of terminal priority planning. Fig. 2 and Fig. 5 proceed interpolation planning trajectory by simulation model of welding robot, it can be seen in the figure that the steps are even and images are verisimilar, it managed to recreate the straight line and curve trajectory, it fully validated the availability and validity of the terminal priority planning method. Through the analysis of data and figures, we could see that the terminal priority planning method successfully completes the trajectory planning of welding robot; it verifies the terminal priority planning method.

Values of the second inverse solutions the third inverse solutions are exactly the same, so the two curves are overlapped.

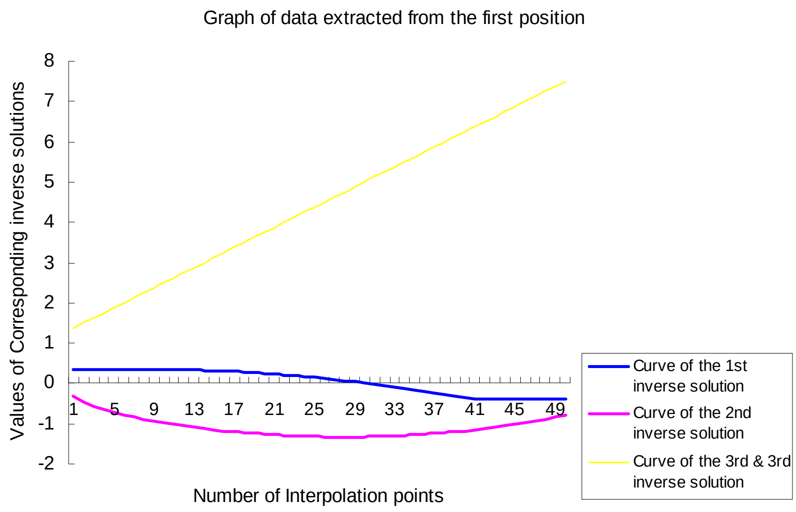

Fig. 3. Graph of data extracted from the first position.

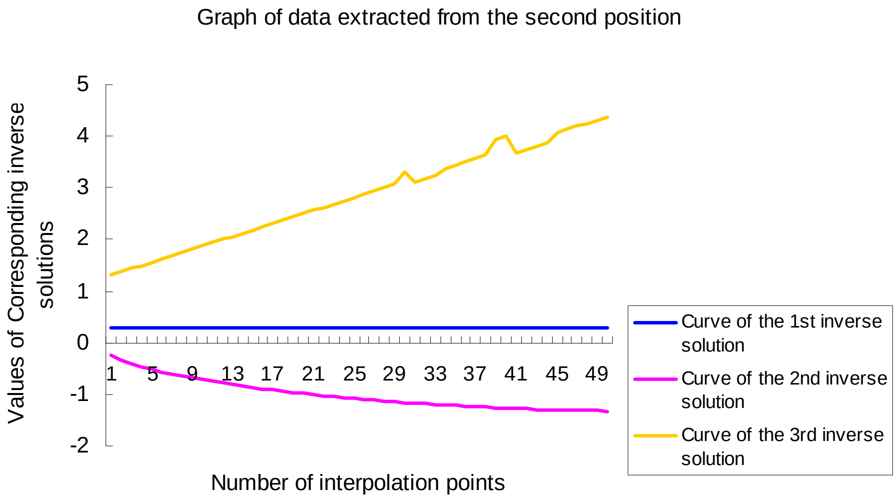

Fig. 4. Data extracted from the second position.

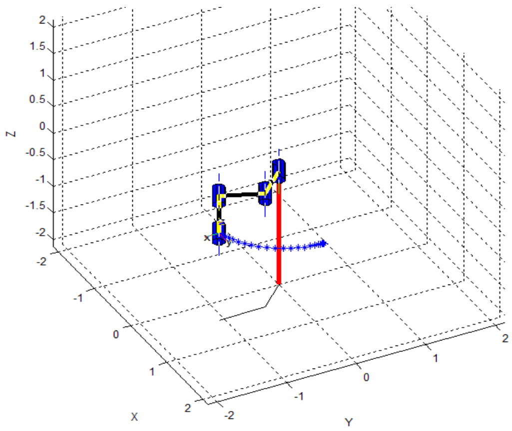

Fig. 5. Trajectory diagram of curve line interpolation.

5. Conclusions

On the basis of the movement feature of multi-joint welding robot and principle of energy configuration, the paper analyzed on energy conservation and improving robot terminal accuracy, it proposed a terminal priority planning method of robot trajectory planning, and solved problems in finding inverse solution of traditional motion equation, it also reduced energy consumption in motor process, improved the fitting precision of robot space trajectory, and realized reasonable and optimized energy distribution of welding robot. The trajectory planning method can not only realize joint-space trajectory planning of welding robot, but also can be applied to other multi-axis systems especially joint-space planning of redundant robots. The experimental data and result demonstrated that the research is of high feasibility and technological application values.

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